Project no. 723678

"The next Generation of Carbon for the Process Industry"

Coordination and Support Action

Theme [SPIRE 5] – Potential use of CO_2 and non-conventional fossil natural resources in Europe as feedstock for the process industry

Deliverable *3.1*: *CO_2/CO availability and price analysis*

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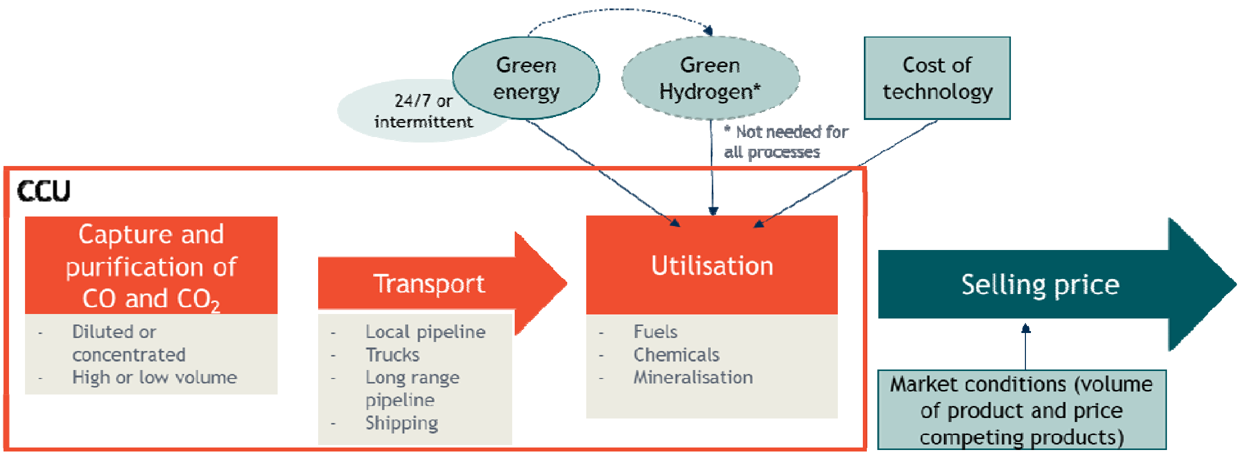
1. Introduction

This deliverable focuses on assessing under which price conditions it is interesting to use CO/CO_2 as feedstock for the process industry. However, it does not analyse the individual pathways for which CO/CO_2 could be used as a feedstock (as selected under WP2), but rather focuses on assessing the attractiveness of using CO or CO_2 in the process industry in comparison to status quo conditions (e.g. using CO for heating or electricity production or emitting CO_2 and paying ETS prices).

Therefore, the scope of this deliverable is only on the capture, purification and transport of CO and CO_2 to be used as feedstock in the process industry; while WP4 will take into consideration the whole business case as depicted below. Given that the utilisation phase is not within the scope, the analysis can be done at a general level, for all pathways selected in WP2, making a split only across CO and CO_2. Where relevant, we have included the forecasts for 2030 (the time frame for which the business case assessment will be carried out).

Figure 1-1 Scope of the CCU business case



Chapter 2 of this deliverable focuses on assessing the availability of CO_2 and CO, expanding on the findings from WP1. Chapter 3 first provides an overview of the eligibility of CCU under the EU-ETS and then assesses the EU-ETS CO_2 prices along with the CO_2 capture and transport costs. Chapter 4, on the other hand, compares the current situation using CO from the steel industry for energy generation with the potential alternative of its use in the process industry. In this case, CO_2 emission prices are subtracted from the gains from electricity generation using CO to assess at what CO_2 emission price CO use for electricity generation would be discouraged.

2. Availability of CO_2 and CO

Deliverable 1.1 under the CarbonNext project mapped the availability of CO_2 and CO in Europe in 2014, based on data from the European Pollutant Release and Transfer Register (E-PRTR) database by the European Environment Agency (EEA).

2.1 Availability of CO_2

Deliverable 1.1 showed the many CO_2 producing sources across Europe that could potentially supply CO_2 as a feedstock for the chemical industry. The attractiveness of a particular CO_2 source with regards to CCS/CCU will depend on its volume, concentration, partial pressure, integrated system aspects and proximity to a suitable process industry that can utilize the CO_2 as a feedstock.[1]

At global level, approximately 76% of CO_2 emissions come from combustion of coal and gas for power generation.[2] It is expected that – due to climate policies – this source of CO_2 will decrease significantly or be phased out by 2100.[3] Further, CO_2 captured from coal and gas power generation plants has a low concentration of 12-14% and can be contaminated with sulphur and heavy metals such as mercury, making capture and purification (clean-up) more expensive. Moreover, the process is associated with efficiency losses of approximately 10 to 30% of the output energy.[4] As such, emissions from the power sector, despite being very large, are not included in the primary target sources.

Sources with higher CO_2 concentrations in the flue gas stream, most preferable pure CO_2, are expected to be more attractive since they offer cost-efficient CO_2 separation when compared to diluted sources. The CO_2 partial pressure of the gas stream to be treated is an additional consideration. In general, the lower the CO_2 partial pressure the more difficult it is to purify the gas stream.[5] Another related important consideration is the energy required for the capture and separation processes. The energy needed will affect both the cost and environmental implications of the process. Sources with high concentration and purity of CO_2 are most viable as in such cases smaller volumes of emitted gas will need to be processed to result in the same amount of purified CO_2 when compared to more dilute sources.

Deliverable 1.1 identified four sources that produce CO_2 in high concentrations and are therefore the focus of this analysis. These are: hydrogen production, natural gas processing, ethylene oxide manufacture and ammonia production. Table 2-1 summarizes the CO_2 concentrations, emission volumes per year and estimated capture costs per tonne of CO_2 captured from a number of CO_2 emitters as presented in Deliverable 1.1. From the table it is already apparent that the lowest capture costs pertain to the most concentrated sources of CO_2.

[1] IPCC (2005) Special Report on Carbon Dioxide Capture and Storage

[2] Naims, H. (2016). Economics of carbon dioxide capture and utilization – a supply and demand perspective. Environmental Science and Pollution Research, 23(22), 22226-22241. https://link.springer.com/article/10.1007%2Fs11356-016-6810-2

[3] Over the medium term, "clean coal" technologies such as integrated gasification combined cycle or pressurized fluidized bed will improve combustion efficiencies; while in the longer-term coal use is expected to be phased out altogether due to climate objectives.

[4] De Ceninck and Benson 2014; Finkenrath 2011 in Naims, H. (2016). Economics of carbon dioxide capture and utilization – a supply and demand perspective. Environmental Science and Pollution Research, 23(22), 22226-22241. https://link.springer.com/article/10.1007%2Fs11356-016-6810-2

[5] IPCC (2005) Special Report on Carbon Dioxide Capture and Storage

Table 2-1 Key sources of CO_2 in Europe. Adapted from E-PRTR and Naims, 2016[6]

CO_2 Source	CO_2 concentration [%]	Emission per year [Mt CO2/year]	Cost [€/t CO_2]	Number of point sources emissions over 0.1 Mt/yr
Hydrogen Production	70-100	5.3	30	15
Natural Gas Production	5-70	5.0	30	10
Ethylene oxide Production	100	17.7	30	6
Ammonia Production	100	22.6	33	27
Paper Pulp Industry	7-20	31.4	58	35
Coal to Power (IGCC)	3-15	3.7	34	3
Iron and steel	17-35	151.3	40	93
Cement	14-33	119.4	68	212
Total		**356.4**		

In addition to the physical properties of the gas stream, CO_2 availability will depend on other considerations such as the geographical accessibility and transport distances between the emitter source and the CO_2 utilizing industry. Furthermore, technology changes will determine future industrial emissions and some industrial sectors will be able to reduce emissions more significantly than others. Market demand and future industrial growth of the emitting sources will also contribute to the availability of CO_2 for CCU. Below we briefly look at outlooks for potential future developments for the selected sources.

2.1.1 Forecasts for hydrogen production market

Currently H_2 **usage** is split roughly 50:50 between hydro-treating/hydro-cracking by refineries and ammonia/nitrogen-based fertilizer production by the chemical industries.[7] Global H_2 market is expected to grow at a compound annual growth rate (CAGR) of 5.99% during the period 2017-2021[8], due mostly to a growing demand for fertilizers.[9] For the European market the annual growth for the H_2 market is expected to be 3.5% up to 2025 with a domestic consumption of 7 Mt in 2015.[10] Around 96% of global H_2 **production** is from steam reforming of methane (SRM), oil-based or from coal gasification.[11] There are 16 SRM facilities in Europe, each emitting between 0.136-0.805 Mt of CO_2 per year.[12] In addition, as presented in Deliverable 1.1 many of these facilities are in close proximity to large European chemical parks. Emissions are expected to increase proportionally to the H_2 market growth.

Without technological progress it is likely that future production of H_2 will come from reforming of natural gas and electrolysis driven by a grid mix inclusive of coal-fired power plants. However, a switch to electrolysis of water using renewable energy (also thought to be a good option to stabilize intermittent green electricity production) will mean that CO_2 availability from this source will decrease significantly.[13]

[6] Naims, (2016) cites US EIA (2014), "Assumptions to the Annual Energy Outlook 2014", Independent Statistics and Analysis for data on ammonia, hydrogen and natural gas production

[7] Naims, H. (2016), Economics of carbon dioxide capture and utilization – a supply and demand perspective. Environmental Science and Pollution Research, 23(22), 22226-22241. https://link.springer.com/article/10.1007%2Fs11356-016-6810-2

[8] TechNavio (2017), Global Hydrogen Generation Market 2017-2021, October 2017

[9] TechNavio (2017), Global Hydrogen Generation Market 2017-2021, October 2017

[10] CertifHy (2015), Overview of the market segmentation for hydrogen across potential customer groups, based on key application areas, June 2015

[11] IEA (2012), Energy Technology Perspectives 2012, IEA

[12] Based on E-PRTR data, as presented in Deliverable 1.1

[13] Other low-carbon technologies such as photocatalytic water-splitting or biohydrogen/fermentative production are further from commercial reality and thus not included in our forecast.

2.1.2 Forecast for natural gas production market

CO_2 emissions from natural gas processing range from 0.1 -1 Mt per year per facility from 10 European facilities. Some of the largest natural gas processing facilities are located in the UK, in close proximity to large chemical parks located in Belgium, the Netherlands and Germany. As shown in Table 2-1 raw natural gas contains different concentrations of CO_2 depending on the source where the gas originates from, however in order to achieve pipeline quality the raw natural gas is often processed by a procedure that includes CO_2 separation.[14] As such natural gas is considered one of the major, high purity, CO_2 sources, requiring no additional purification cost in the carbon capture process. Natural gas processing (and therefore CO_2 availability from this source) is expected to increase in the medium term as power generation shifts away from coal and natural gas is used to balance intermittent renewable generation.

2.1.3 Forecast for ethylene oxide production market

Ethylene oxide is used as an intermediate product to produce many industrial chemicals including polymers and ethylene glycols. Ethylene oxide itself is used as a fumigant, disinfectant and sterilant for medical purposes. Six ethylene oxide facilities producing more than 0.1 Mt CO_2 per year per facility are listed on E-PRTR producing a combined emission of 17.7 Mt/yr of CO_2.[15] The ethylene oxide production facilities in Europe are located in Belgium, the Netherlands and Germany, all of which also have large chemical parks which could potentially utilize the CO_2 as feedstock. According to Market Reports high ethylene oxide production demand is expected by 2022.[16]

2.1.4 Forecast for ammonia production market

The European fertilizer market is expected to have a steady CAGR of 2.5% over the forecast period of 2017-2022.[17] CO_2 emissions from ammonia production in Europe amounted to 22.6 Mt in 2014, coming from 27 facilities with emissions from 0.1-3.2 Mt per year per facility. A number of these facilities are located in proximity of chemical parks as shown in Deliverable 1.1. Ammonia is predominantly used as a fertilizer and is produced via the Haber process. CO_2 is produced during the production of hydrogen which is combined with nitrogen to produce ammonia. A report by the International Fertiliser Association shows that around 36% of the CO_2 removed from the syngas in the clean-up step is utilized by industry. Around 33% of this CO_2 is used for urea production, whilst the remaining CO_2 is sold for other uses.[18] Hence, availability for CCU in the case for ammonia could be limited as there would be competition with the current CO_2 uses for urea production.

Conclusion: Even if, in the longer run the use of natural gas (and thus the availability of CO_2 from cleaning it) or steam reformed hydrogen production will decrease, we expect that the amounts from these four CO_2 sources will remain the most attractive by 2030. Further, volume-wise, we expect them to be large enough to cover CCU demands. If by 2030 the deployment of CCS technologies becomes operational, the CO_2 intended for storage could instead become a very cheap source of CO_2 for CCU if it is equally accounted in comparison to CCS in the EU-ETS.

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[14] Baker, RW and Lohhandwala K (2008) "Natural gas processing with membranes: an overview" Ind Eng Chem Res 47:2109-2121 in Naims, H. (2016). Economics of carbon dioxide capture and utilization – a supply and demand perspective. Environmental Science and Pollution Research, 23(22), 22226-22241. https://link.springer.com/article/10.1007%2Fs11356-016-6810-2

[15] ICIS lists a total of 12 plants in Europe (source: https://www.icis.com/resources/news/2013/04/13/9658385/chemical-profile-europe-ethylene-oxide/), but it is presumed that the other six facilities have emissions of less than 0.1 MT/year.

[16] https://factsweek.com/289490/ethylene-glycol-and-ethylene-oxide-market-report-2017-scrupulous-details-of-market-expandation-with-high-production-demand-forecast-by-2022/

[17] Mordor Intelligence, https://www.mordorintelligence.com/industry-reports/europe-fertilizers-market?gclid=Cj0KCQjwqM3VBRCwARIsAKcekb2UeWMFz5758xh80N_17i20nRrKe0OASR0KH0Y6kVqGqOelJMrA4wQaAju-EALw_wcB

[18] GCCSI (2010) Carbon capture and storage in industrial applications: technology synthesis report, http://www.globalccsinstitute.com/publications/carbon-capture-and-storage-industrial-applications-technology-synthesis-report

2.2 Availability of CO

CO is another important source of carbon that could be used as feedstock in the chemical industry. Deliverable 1.1 mapped the most important sources of CO emissions. The total CO emissions for all European countries in 2014 was 3.38 Mt. The metal sector was the main contributor to CO emissions, accounting for 71% of the total CO emissions, of which 92% (2.2Mt) comes from the manufacture of basic steel and ferro-alloys.

The carbon content in the waste gases[19] produced by the steel industry typically consists of 15-25% CO_2 and 18-30% CO. CO is much more reactive than CO_2, and is therefore a more attractive option in terms of its use as feedstock for other chemical transformations.[20] However, in the process of extracting the CO from the waste gas the gas will be enriched in CO_2, in other words this will result in the cleaning up of waste gases such that the concentrated stream of CO_2 could also be used for CCS or CCU.

CO is not allowed to be discharged into the atmosphere thus, in the steel production process it is usually reused for on-site heating processes or for electricity production (due to its high calorimetric valorization of 556 kJ/mol). In fact, much more CO is produced than the amount emitted by a steel mill, because a large proportion of the electricity and steam required in the steel production process is produced from steel mill gases. However, it is now being considered whether converting this CO into carbon-based products would be more beneficial than using it for electricity or steam production. The potential amount of CO available could be higher by a factor of 12-20, if the CO which is currently used for electricity and stream production was also taken into account.

Looking Forward

Changes in steel production which may have an effect on CO emissions depend on the underlying technological developments. There are a few new and promising developments (like the HIsarna project)[21] that could reduce the CO/CO_2 output from steel production substantially. However, these developments are not expected to impact the industry considerably by 2030.

[19] Waste gases refer to the by-product gases produced by industry. In the case of the steel industry three types of cases are mainly produced: coke oven gas, blast furnace gas and basic oxygen furnace gas.

[20] CarbOn-monoxide RE-use through industrial SYMbiosis between steel and chemical industries, November 2017

[21] HIsarna is a breakthrough technology for producing steel which leads to enormous efficiency gains. It reduces energy use and CO2 emissions by 20% and reduces the emissions of fine particles, sulphur dioxide and nitrogen oxide with between 60 to 80%. The gases that leave the reactor are concentrated CO_2. So far 75 million euros have been invested in developing HIsarna.

Source: https://www.tatasteeleurope.com/en/innovation/hisarna/about-hisarna

3. CO_2 for CCU processes

This chapter first briefly addresses the eligibility of including CCU under the European Union Emission Trading System (EU-ETS), as this would represent an important incentive for its deployment. Then it looks at the overall costs of supplying CO_2 for use in industry by assessing the CO_2 prices under ETS and the costs of CO_2 capture and transport.

3.1 Eligibility of CO_2 use in CCU processes under ETS

Currently, utilising CO_2 falls outside the accounting scope of the EU-ETS. The EU-ETS Monitoring and Reporting Regulation (MRR Regulation) states that the transfer of inherent or pure CO_2 shall only be allowed for the purpose of **long-term geological storage**.[22] Utilising the CO_2 for any other purpose would require the emitter to surrender emission allowances for the utilised CO_2 and is therefore not financially encouraged.

A reform of the narrow focus of Article 49 of the MRR Regulation has been debated in several occasions.[23] Such a reform would be in line with the Energy Union Package[24] which acknowledges CCS and CCU within its Research, Innovation and Competitiveness Dimension stating that *"A forward-looking approach to CCS and CCU for the power and industrial sectors, which will be critical to reaching the 2050 climate objectives in a cost-effective way. This will require an enabling policy framework, including a reform of the Emissions Trading System…"*

A legislative proposal to revise the EU-ETS was presented in 2015 including the following amendment: "*The main long-term incentive from this Directive for the capture and storage of CO_2 (CCS), new renewable energy technologies and breakthrough innovation in low-carbon technologies and processes is the carbon price signal it creates and that allowances will not need to be surrendered for CO_2 emissions which are permanently stored or avoided.*"[25] As can be read, the proposal extends the scope of the EU-ETS Directive by including (1) low-carbon technologies and processes in industry; and (2) allowances will not need to be surrendered for CO_2 emissions which are 'permanently stored or avoided', which potentially makes room for CCU. However, the actual meaning and interpretation of these two concepts still require clarification.

It is argued that those forms of CCU which lead to permanent storage of CO_2 (such as mineralisation routes) should be included in the EU-ETS reporting framework.[26] The SCOT project proposed, for example, to amend the MRR such that it would include mineralisation routes which meet certain CO_2 storage requirements, such as longevity of the product. And indeed, in the course of the amendment of the Emissions Trading Directive 2003/87/EC (EHRL) for the fourth trading period at European level, there is currently increased discussion about the use of CCU and its consideration. The political debate is fuelled by the European Court of Justice (ECJ) ruling on Schäfer-Kalk of 19 January 2017 (C-460/15). The ECJ followed Schäfer-Kalk's view that the process in question for the production of precipitated calcium carbonate from emitted CO_2 leads to a permanently stable chemical compound and is therefore not to be regarded as an emission within the meaning of Article 3(b) of Directive

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[22] Article 49 of the EU-ETS Monitoring and Reporting Regulation 601/2012

[23] C and CEFIC (2015) scoping workshop "Transforming CO2 into value for a rejuvenated European economy"; UN (2015) Climate Action Now: Summary for Policymakers 2015; DG JRC and CLIMA (2013) CO2 re-use workshop; Trinomics, Ricardo-AEA, and TNO (2015) Support to the review of CCS Directive; DG ENV, 2012, Use of Economic Instruments and Waste Management Performances – Final Report, p. 179

[24] COM (2015) 80– Energy Union Package. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy

[25] COM(2015) 337 - Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low carbon investments

[26] Zero Emissions Platform (2016), ZEP Policy Brief: CCU in the EU-ETS; SCOT project. Briefing paper: EU-ETS to incentivise CO2 utilisation?

2003/87. For the purposes of the Directive, "emissions" means the release of greenhouse gases into the atmosphere from sources in an installation. Accordingly, the methodology for the monitoring of installations specific to activities (Article 20(2)) set out in Annex IV to Regulation No 601/2012, Section 10 on "Production of lime or calcination of dolomite or magnesite in accordance with Annex I to Directive 2003/87/EC": "If CO_2 is used in the plant or transferred to another plant to produce precipitated calcium carbonate (PCC), this quantity of CO_2 shall be considered as emissions from the plant producing the CO_2". This precedent case raises the question of how different CO_2 usage paths are to be evaluated, classified and prioritised with regard to deductibility in the fourth trading period according to transparent and comprehensible criteria.

In 2017, the Council endorsed the reform of the EU-ETS for the period after 2020.The reform is mainly focused on reducing the cap on the total volumes of emissions and changes to the market stability reserve (MSR) system. As discussed in section 3.2 below these changes will have an effect on the price of ETS and thus indirectly affect the viability of CCU. However, no major changes to Article 49 of the MRR Regulation have been made.[27]

3.2 Key costs regarding CO_2 for CCU

In order to provide a rough assessment of the costs associated with supplying CO_2 for CCU we look at the CO_2 price under the EU-ETS as well as the costs of its capture and transport.

3.2.1 ETS CO_2 price

ETS prices have been too low for them to effectively cut emissions and incentivise low-carbon investments. The figure below indicates the decreasing ETS price (from almost 30 EUR/t CO_2 in 2008 to 2.46 EUR/t CO_2 in 2013), suggesting that it generally remained too low to stimulate sufficient investments in technologies that would avoid CO_2 emissions.[28] For this reason the EU-ETS reform aims to make changes in order to encourage further emission reductions disincentivizing the production of GHG and promoting innovation and the use of low-carbon technologies.

[27] The Innovation fund will be an extension of the NER300 facility. It will consist of 400 million allowances coming from free allocation and auctioning. The fund will have the possibility to expand by an additional 50 million allowances. Source: Reform of the EU emission trading system – Council endorses deal with the European Parliament, 22/11/2017, Press release 632/17

[28] RAP Online (2017). Efficiency first in the Energy Union. http://www.raponline.org/wp-content/uploads/2017/11/rap-openexp-eb-ys-efficiency-first-energy-union-2017-nov-20.pdf;

Figure 3-1 Evolution of ETS price development from 2008 to 2015. Source: EDF (2015)[29]

It is estimated that carbon prices of US$40-80/t$CO_2$eq by 2020 and US$50-100/tCO_2eq by 2030 are needed to achieve the Paris Agreement goals.[30] The ETS reform for the 2021-2030 period is intended to improve its overall functioning.[31]It aims to increase the ETS price over the medium to long-term. Key changes include:

- An annual 2.2% reduction to the cap on total emissions.
- The temporary doubling (until the end of 2023) of allowances in the market stability reserve (MSR).
- A new mechanism (operational in 2023) that limits the validity of allowances in the MSR.[32]

Emissions trading is based on the stock market and precise forecasts of future prices are difficult. In March 2018, the price of CO_2 was approximately 11 EUR/t CO_2eq. Estimates for 2030 range from 11-75 EUR/tCO_2 eq by 2030 and from 85-264 EUR/tCO2eq by 2050 depending on the scenario.

The ETS price is estimated at around 30 EUR/t CO_2[33] in 2030 and 90 EUR/t CO_2 in 2050 under the EU Reference Scenario 2016. The OECD/IEA 450 scenario estimates 75 EUR/t CO_2eq by 2030.[34] The

29 EDF (2015), European Union. The World's Carbon Markets: A Case Study Guide to Emissions Trading. Available from: http://www.ieta.org/resources/Resources/Case_Studies_Worlds_Carbon_Markets/euets_case_study_may2015.pdf

30 Carbon Pricing Leadership Coalition (2017). Report of the High-Level Commission on Carbon Prices. https://static1.squarespace.com/static/54ff9c5ce4b0a53decccfb4c/t/59b7f2409f8dce5316811916/1505227332748/CarbonPricing_FullReport.pdf & Carbon Market Watch (2017). Policy briefing - Pricing carbon to achieve the Paris Goals. Available from https://carbonmarketwatch.org/wp/wp-content/uploads/2017/09/CMW-PRICING-CARBON-TO-ACHIEVE-THE-PARIS-GOALS_Web_spread_FINAL.pdf

31 European Commission (2018). Website ETS Revision for phase 4 (2021-2030), https://ec.europa.eu/clima/policies/ets/revision_en

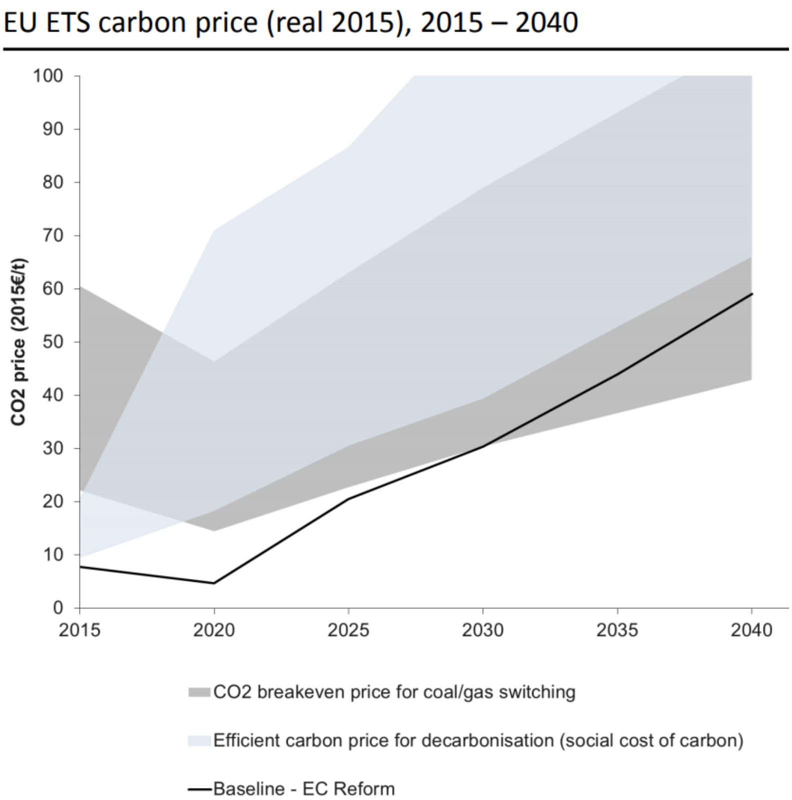
32 In addition, it states that the new ETS provisions will be kept under regular review and adjusted if additional policy measures are needed to achieve the Paris Agreement commitments. Source: Reform of the EU emission trading system – Council endorses deal with the European Parliament, 22/11/2017, Press release 632/17 http://www.consilium.europa.eu/en/press/press-releases/2017/11/22/reform-of-the-eu-emissions-trading-system-council-endorses-deal-with-european-parliament/

33 This is in accordance with reported estimates by market specialists. See: http://carbon-pulse.com/43132

34 450 scenario assumes a $140/tonne price by 2040. OECD/IEA (2015), WEO Special Report Energy and Climate Change

ETS prices estimated in the latest impact assessment, based on various policy scenarios, range between 11 to 53 EUR/t CO_2 by 2030 and 85 to 264 EUR/t CO_2 by 2050.[35]

Figure 3-2 EU ETS carbon price, 2015-2040[36]



3.2.2 Carbon capture costs[37]

CO_2 carbon capture costs include fixed costs (such as purchase of equipment, including 'scrubbers') and variable costs (including the purchase of chemicals necessary to absorb emissions generated, labour costs and expenditure on replacement equipment). CO_2 capture technologies, however, are still not fully developed and often used on a small scale. Thus, cost-reduction considerations are crucial in assessing the viability of CCU on a large industrial scale.[38]

There are two main ways of reporting carbon capture costs: by reporting costs of capture or by reporting costs of avoidance of CO_2. Cost of CO_2 captured, refers to the capture cost per amount of CO_2 captured. Cost of CO_2 avoided, on the other hand, estimates the CO_2 emission reduction by

[35] EC (2014), Impact Assessment accompanying the document: A policy framework for climate and energy in the period from 2020 up to 2030. http://ec.europa.eu/smart-regulation/impact/ia_carried_out/docs/ia_2014/swd_2014_0015_en.pdf

[36] "Carbon pricing in Europe after the ETS reform and Brexit" F. Roques, Compass Lexecon and University Paris Dauphine

[37] The processes and technologies used for carbon capture are, in principle, the same for CCS and CCU. Since CCS is more widely discussed in the literature some of the data presented is taken from literature pertaining to the CCS process.

[38] Naims, H. (2016). Economics of carbon dioxide capture and utilization – a supply and demand perspective. Environmental Science and Pollution Research, 23(22), 22226-22241. https://link.springer.com/article/10.1007%2Fs11356-016-6810-2

comparing the captured CO_2 to the emissions of a reference plant without CCS (CCU) technology.[39] Both are expressed in EUR/ tCO_2 per year. The following formulas describe the indicators:[40]

$$cost\ of\ CO2\ captured\ \left(\frac{€}{tCO2}\right) = \frac{additional\ costs\ of\ CO2\ capture\ (€)}{amount\ of\ CO2\ captured\ (tCO2)}$$
$$= \frac{costs\ plant\ including\ capture(€) - costs\ reference\ plant(€)}{amount\ of\ CO2\ captured\ (tCO2)}$$

$$cost\ of\ CO2\ avoided\ \left(\frac{€}{tCO2}\right) = \frac{additional\ costs\ of\ CO2\ capture\ (€)}{amount\ of\ CO2\ reduction\ (tCO2)} = \frac{costs\ plant\ including\ capture(€) - costs\ reference\ plant(€)}{CO2\ emitted\ ref.plant\ \ (tCO2) - CO2\ emitted\ capt.plant\ (tCO2)}$$

Cost of CO_2 captured better reflects the worth of carbon capture technologies as “industrial commodities” because it shows whether it will be economically viable to capture CO_2 given a market price for CO_2. On the other hand, the cost of CO_2 avoided reveals the amount of actual emission reductions and thus is a better indicator to measure environmentally relevant information. The overall cost of carbon capture will depend on a number of variables, of which the most relevant ones are discussed below.

Costs of capture based on capture technology

The costs of carbon capture vary depending on the capture technology employed at the particular facility. The choice of technology is intrinsically linked to the chain of technical, economic, legal, environmental and health and safety aspects. An overview of the main CO_2 capture technologies was presented in Deliverable 1.1. These technologies are briefly presented below.

- **Pre-combustion carbon capture** works by the gasification (rather than combustion) of fuel to produce syngas, (a mixture of gases consisting predominantly of CO and H_2). The CO is then converted into CO_2 via a shift reaction with water. This process generates additional H_2.
- **Post-combustion carbon capture** is usually used to retrofit existing power plants. The technology is based on CO_2 trapping by chemical solvents in order to separate them from other elements present in the flue gases.
- **Oxyfuel carbon capture** is based on the combustion of fossil fuels in the presence of pure oxygen. This results in an exhaust gas that is CO_2-rich thus facilitating the capture process.

Carbon capture technologies offer contrasting levels of purification, with combustion plants implementing oxyfuel displaying the largest range of CO_2 impurities, whilst post-combustion capture plants result in the purest CO_2 (varying per technology).

Carbon capture technologies are still in the early stage of development and substantial improvements in efficiency are expected. In addition, “new generation” technologies are also being developed. The technological developments will be an important driver in cost-reduction and economic viability of CCS and CCU.

Costs of capture from fossil-based power generation

The Zero Emissions Platform (ZEP) has produced estimates for carbon capture costs from fossil-based power generation in the context of CCS (covering hard coal, lignite and natural gas).[41] .

[39] Since the process of capturing CO_2 requires an energy input and usually decreases the plant’s efficiency, the process of capturing itself produces CO_2 emissions. Based on this the amount of CO_2 avoided (compared to a reference system) is typically smaller than the amount of CO_2 captured.

[40] Naims, H. (2016). Economics of carbon dioxide capture and utilization – a supply and demand perspective. Environmental Science and Pollution Research, 23(22), 22226-22241. https://link.springer.com/article/10.1007%2Fs11356-016-6810-2

[41] Although the report was produced in 2011 it continues to be one of the most comprehensive studies on the costs of carbon capture available to date and provides important references for understanding present and future trends. Note that, as discussed previously, based on the need to reduce GHG emissions, it is expected that the use of hard coal and lignite will decrease substantially or be phased out in the mid- to long-term. However, natural gas is expected to play an important role as coal-substitute during the transition to a renewable energy-powered future.

Table 3-1 CO_2 avoidance cost in EUR per tonne CO_2*

	Average cost	Min cost	Max cost
Hard Coal PF Post-Combustion Capture	33.3	28.5	37.2
Hard Coal IGCC with Pre-Combustion Capture	39.8	33.3	48.3
Hard Coal PF Oxy-Fuel	-	29.9-39.3	42.1-58.2
Lignite PF Post-Combustion Capture	-	-	38.9
Lignite IGCC with Pre-Combustion Capture	-	-	29.9
Lignite PF Oxy-Fuel Capture	-	19.3	-
Natural Gas CCGT Post-Combustion Capture	-	79.0	109.7

*Figures are based on second quarter 2009 equipment cost levels. Capture costs are defined as the costs related to the capture process plus the costs of compression/liquification of the captured CO_2 that are required for transport. Fuel cost assumptions are 2.4 EUR/GJ for hard coal and 8 EUR/GJ for natural gas.

Costs of capture based on high-purity sources

As discussed in section 2.1, the purity of the CO_2 is an important factor to be taken into consideration. Higher purity translates to higher CO_2 concentrations per equal amounts of volumes, and therefore lower costs. The purity also has implications in compatibility with certain transport and storage applications as impurities can inflict damages to pipelines, whilst leading to complications in compressing the mixture.

The table below provides an overview of estimated capture costs per high-concentration source (as identified in section 2.1).

Table 3-2 CO_2 capture cost in EUR per tonne CO_2 per source. Source: Naims 2016*and IPCC 2015

Industrial Process	Capture Cost (€$_{2014}$/tCO_2)	CO_2 content (vol.%)	CO_2 partial pressure (MPa)
Ethylene oxide production	30	100	0.3
Ammonia production	33	100	0.5
Hydrogen production	30[42]	70-90	0.3-0.5
Natural gas production	30[43]	5-70	0.05-4.4

**For ammonia, hydrogen and natural gas production figures it is assumed that CO_2 is compressed for pipeline transport to ~ 9-120 bar and a CO_2 purity of ≥95% can be assumed. 85-100% capture rates are assumed. The costs include compression costs and regional transport costs (for EOR/EGR purposes)*

3.2.3 Costs of carbon transport

CO_2 must be transported from the capture points to the destination sites. Transportation costs vary based on the distance to be transported (which affects the type of transport, i.e. shipping, trucks, local or long-range pipelines). In the case of pipeline transport, costs further vary depending on pipeline length and diameter, construction material used and the route of the pipeline. The most cost-effective

[42] The IPCC (2005) Special Report on CO_2 Capture and Storage reports H_2 prices in the range of 2.2 to 38.9 USD/tCO_2 depending on the production process. Some processes include H_2 production in conjunction with electricity generation.

[43] This value is in accordance with capture costs of 27.3 USD/tCO_2 and 25 UDS/tCO_2 for Germany and Poland respectively as reported by the GCCSI (2017), Global Costs of Carbon Capture and Storage.

means of transportation involves using existing infrastructure which can be further streamlined via sharing the transportation network to encourage economies of scale.[44] A shared CO_2 transportation network can also alleviate purity issues by allowing a mixture of sources to provide a final CO_2 product that is suitable.

The table below provides an overview of estimated CO_2 transport costs, depending on the type of transport infrastructure and distance for a capacity of 2.5 million tonnes CO_2 per year using point-to-point connections. These volumes are more representative of CCS than CCU, and are provided as reference.

Table 3-3 Cost estimates for CCS demonstration projects, 2.5Mt per annum (EUR/tonne CO_2). Source: ZEP (2011)

Distance	180km	500km	750km	1500km
Onshore pipe	5.4	NA	NA	NA
Offshore pipe	9.3	20.4	28.7	51.7
Ship[45] (including liquification)	13.5	14.8	15.9	19.8

3.2.4 Assessment

This report provides a rough assessment of the ETS price and the capture and transport costs. WP4 will provide a more detailed business case assessment, taking into account, among other pathway specific aspects, the selling price of the product. However, in this report, we assume a positive stimulus for CCU when CCU is included under the ETS scope and the ETS price is higher than the combined capture and transport cost (or expectations of this in the future). Current carbon prices under the EU-ETS of ~ 11 EUR/tCO_2 are too low to be supportive. Thus, in what follows we focus the discussion on forecasts for 2030.

In table 3-4 we use transport values related to onshore pipelines for distances of 180 km, in line with the premise that most CCU projects will aim to minimize transport distances (at least in the near future).[46]

Table 3-4 Assessing ETS forecasts and costs of carbon capture and transport. Prices in EUR/tCO_2

	ETS price (2030 forecast)	Capture	Transport[47]	Capture + Transport	Unit
Ethylene oxide production	32 (Low) – 75 (High)	30	5.4	35.4	EUR/tCO_2
Ammonia production	32 (Low) – 75 (High)	33	5.4	38.4	EUR/tCO_2
Hydrogen production	32 (Low) – 75 (High)	30	5.4	35.4	EUR/tCO_2

[44] Araujo & Medeiros (2017), Carbon Capture and Storage Technologies

[45] Proposed costs are also in line with Roussanly et al., (2013), who estimate the costs for ship transport over 480 km without liquification on 7.7 EUR/tCO2 for transporting 15.45 MtCO2/y to an onshore harbor.

[46] Deliverable 1.1 identified European chemical parks in proximity to the major point sources of CO_2 emission. It was argued there that CO_2 sources located close to current process industries are highly desirable as they reduce the transport costs. Deliverable 2.2 further focused on industrial symbiosis where the distances between the CO_2 supplier and the utilizer are ideally short.

[47] Onshore pipe, 180 km, 2.5 Mt per annum

	ETS price (2030 forecast)	Capture	Transport[47]	Capture + Transport	Unit
Natural gas production	32 (Low) – 75 (High)	30	5.4	35.4	EUR/tCO_2

From table 3-4 it is apparent that the lower forecast for ETS prices in 2030 are almost the same as the costs of capture and transport; while the higher forecast for ETS prices are almost double the capture and transport costs. It is important to keep in mind that the figures for carbon capture and transport refer to available present values and are expected to decrease as technology progresses.

4. CO for chemical processes

This chapter focuses on the conditions under which the use of CO for chemical production is attractive. As defined in Deliverable 1.1, we focus on the steel industry, which is the main CO emitter. A comparison is made between the use of CO for the process industry versus its use to generate electricity. This is done by comparing the electricity prices to the CO_2 prices under ETS. Performing a rough assessment and disregarding the price of the final product, using CO for chemical purposes is an attractive option when the costs of emitting CO_2 (from the electricity generation) are higher than the monetary savings from self-generating electricity.

From the perspective of the steel industry, CO is valuable as it can be sold. In addition, selling CO represents diminished emission trade costs as the sold CO gas is not burned into CO_2. However, the sold CO will no longer be used to generate electricity and this source of electricity must be replaced by purchased or otherwise produce electricity.

Thus, in order to assess whether CO as a feedstock for the chemical industry can be economically valuable it is necessary to consider the costs of CO_2 emissions trading and electricity. Using CO for the chemical industry is an attractive option when it's unfavourable to use CO for electricity generation because the cost of emitting CO_2 under the ETS (from the electricity generation) are higher than the energy costs avoided by generating own electricity.

Understanding energy generation from blast furnace gases in the steel industry[48]

Steel production disposes three different gas types: coke gas, blast furnace gas and converter gas. Of this, converter gas has the highest CO content and calorific value.[49] It consists of about 65% CO, 15% CO2, 15% nitrogen and small amounts of hydrogen and methane. Per tonne of coke that is produced, approximately 470Nm3 of coke gas are produced of which around 60% is used for internal processes. The remaining part can be used for power generation resulting in approximately 400kWh.

4.1 Impact of electricity price on CO use

As mentioned above, CO in the steel industry is used for heat and electricity generation. Estimates of how much waste gases are used in the electricity production for the steel industry range from around 25% for all steel waste gases to 50% for all blast furnace gases[50]. Using waste gases for electricity generation results in savings as this electricity does not have to purchased. Assuming 40% of the waste gas is used, it can generate approximately 400 kWh per tonne of coke produced. The resulting savings can be quantified using the current and projected electricity prices.

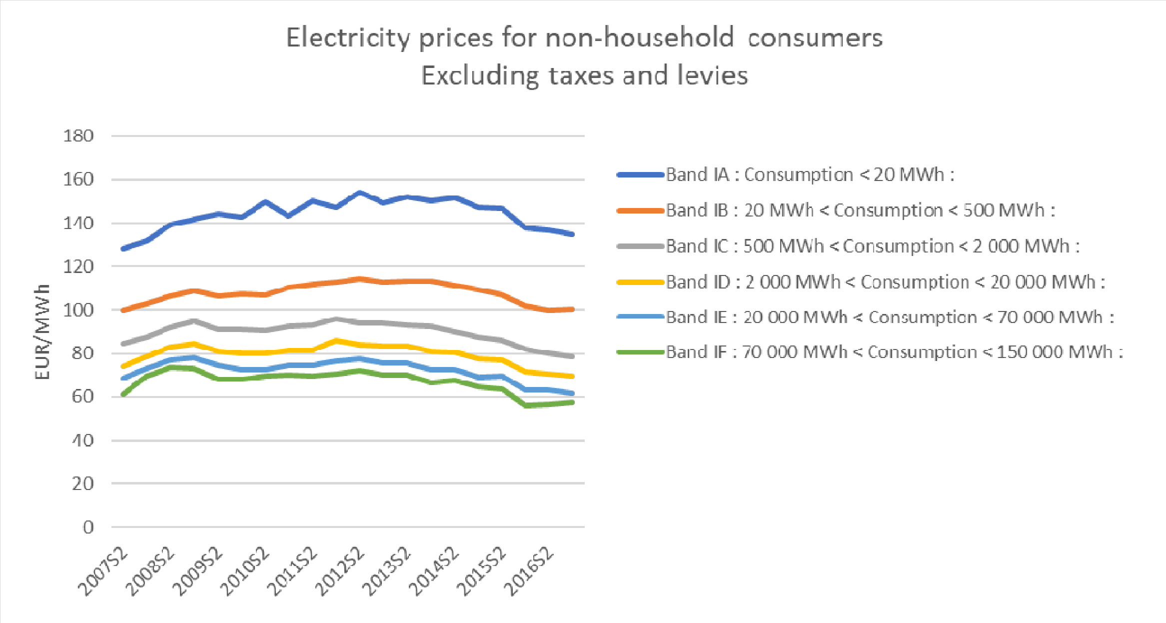
Industrial electricity prices have ranged between 56 and 154 EUR/MWh in the last ten years. The steel industry, consumes very high quantities of electricity and thus is able to negotiate substantial price reductions. We assume that steel falls under the highest consumption band, where electricity prices have ranged between 56 and 74 EUR/MWh.

[48] Clarke Energy, Steel Production Gases. Available at: https://www.clarke-energy.com/wp-content/uploads/Steel-Production-Gases.pdf

[49] **Coke gas** has a calorific value of 5kWh/Nm3 and mainly consists of hydrogen (50-60%), methane (15-50%) and a small percentage of CO, carbon and nitrogen. **Blast furnace gas** has a very low heating value of around 0.9kWh/Nm3 and has a content of around 20% CO.

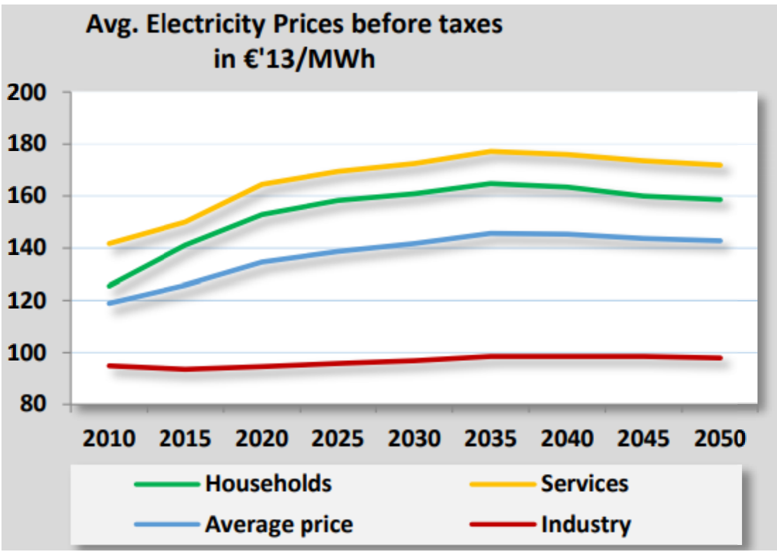
[50] Handler et al., 2016 and Ecofys, 2009 in Metabolic et al (2017), CORESYM: CarbOn-monoxide RE-use through industrial SYMbiosis, November 2017

Figure 4-1 Industrial electricity prices for EU28 (excluding taxes and levies). Source: Eurostat nrg_pc_205



According to the EU Reference Scenario 2016 [51], electricity prices are expected to increase in the coming years. However, the increase is less pronounced for industrial prices, as seen in figure 4-2. Based on this, we assume a potential increase of 5% by 2030. For the highest consumption band, this would imply prices around 59 and 78 EUR/MWh. These are in line with estimates for German industrial consumer, which are of 66 EUR/MWh by 2030.[52] However, for a sensitivity analysis, the average 2030 price for electricity before taxes from the EU Reference Scenario can be used (140 EUR/MWh).

Figure 4-2 Price of electricity by sector. Source: Figure 50 in EU Reference Scenario 2016



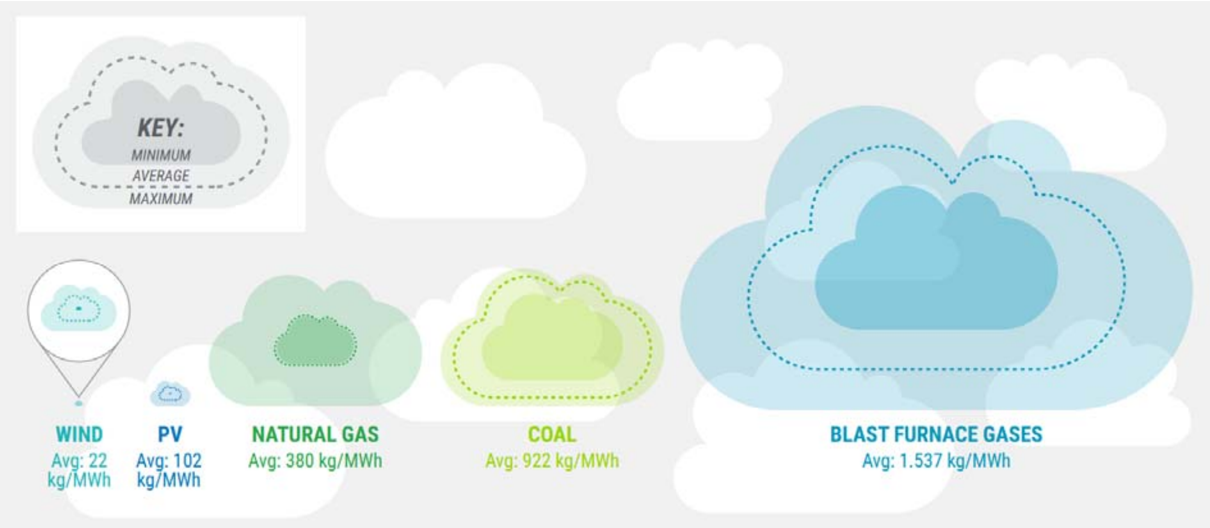
[51] EC (2016), EU Reference Scenario. https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

[52] Fuel Cells and Hydrogen Joint Undertaking (2015), Study on hydrogen from renewable resources in the EU.

4.2 Impact of CO_2 price (ETS)

As seen from Figure 4-3, blast furnace gases are not very valuable energy sources as compared with natural gas or even coal as they produce significantly more GHG emissions per energy of unit generated. These emissions have a monetary penalty based on the ETS. On average blast furnace gases produce 1 537 kg of CO_2eq per MWh of electricity generated[53]. These emissions would fall under the EU ETS.

Figure 4-3 Overview of CO_2eq emissions for electricity from different sources. Source: CORESYM (2017)



As mentioned in the previous chapter, ETS CO_2 prices in March 2018 were around 11 EUR/t CO_2eq; while they are expected to be between 32 EUR/t CO_2eq (as defined in the EU's reference scenario[54]) and 75 EUR/t CO_2eq (as defined by the OECD/IEA 450 scenario[55]) by 2030.

[53] Metabolic et al (2017), CORESYM: CarbOn-monoxide RE-use through industrial SYMbiosis, November 2017

[54] EC (2016), EU Reference Scenario. https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

[55] Based on 450 scenario, which assumes a $140/tonne price by 2040. OECD/IEA (2015), WEO Special Report Energy and Climate Change

4.3 Assessment

The table below compares the savings and the cost of the emissions (from the electricity generated) and states the different assumptions used as explained in the sections above. Only when the CO_2 price is high there is an opportunity for CCU development, as it is no longer profitable to generate electricity. With current prices, a CO_2 price of around 38 EUR/t CO_2eq would be needed to make the CCU case interesting. The most favourable scenario for CO would be a high ETS price and a low electricity price, where the ETS costs would outweigh the electricity savings by 22.5EUR per tonne of coke produced.

Table 4-1 Assessment for CO in EUR/tonne of coke produced. Source: Own calculations

	Savings from electricity generation	Costs from emissions under ETS	Cost/savings from electricity generation
Current prices	23.2	6.8	16.4 (savings)
2030 – Low prices	23.6	19.7	3.9 (savings)
2030 – High prices	31.2	46.1	**14.9 (costs)**

Assumptions:

- 40% of coke gas used for electricity generation
- 400kWh / tonne of coke produced
- 1537 kg of CO_2eq/MWh generated from blast furnaces gases
- The emission costs are calculated by multiplying the emission factor (1.537 kg CO_2eq/kWh) by the electricity produced (400kWh) and then by the CO2 price.
- *Electricity prices:*
  - 58 EUR/MWh in 2017 (Band IF, excluding taxes)
  - 59-78 EUR/MWh by 2030
- *CO_2 prices:*
  - 11 EUR/t CO_2eq in 2018
  - 32-75 EUR/t CO_2eq by 2030

If the CO was used in the chemical industry, there could be an additional value for the CO. The steel industries could therefore sell their CO (CO value), avoid the ETS payments (CO2 value) but pay for electricity from the grid instead of generating and using their own (electricity cost). The alternative economic impact would be calculated as follows[56]:

Economic Impact = CO value + CO_2 value - Electricity cost

Value of CO gas

If the steel industry were to sell its CO emissions, the price would be competitive with the CO price available from other sources. Arvola et al. calculate that the CO price ranges from 11.3 to 21.7 $/GJ. When converted into €/1000 normal m^3 this amounts to ~ 150 €/1000 Nm^3 [57]. A cylinder containing 103 litters of CO in 100 ppm/ air currently costs $ 160.[58]

[56] As defined in Arvola et al (2011), Combining Steel and Chemical Production to Reduce CO_2 Emissions., Low Carbon Economy, 2011,2, 155-122

[57] Arvola et al (2011), Combining Steel and Chemical Production to Reduce CO_2 Emissions., Low Carbon Economy, 2011,2, 155-122

[58] NorLAB, http://www.norlab-gas.com/15m7/gases-cylinders/carbon-monoxide-co.html

5. Conclusion

This deliverable focused on assessing the conditions under which it is interesting to use CO/CO_2 in the process industry.[59] For CO_2 utilization. this was done by assessing current and forecasted CO_2 emission prices under the EU-ETS and the costs of carbon capture and transport. In the case of CO utilization, CO_2 emission prices were subtracted from the gains from electricity generation using CO to assess at what CO_2 emission price CO use for electricity generation would be discouraged.

Without taking into account the product price, utilization of neither CO_2 nor CO in the process industry is attractive under the present ETS and electricity prices. In the case of CO_2 utilization, CCU would need to be included in the ETS scope and the minimum ETS price of emission allowances should reach ~ 35 EUR/tCO_2 in order for investors in CCU to get a positive input in the business case. This price could be attained by 2030 in a low-price scenario and in an optimistic scenario the emission allowances could be as high as 75 EUR/tCO_2. In the case of CO utilization it has been calculated that a CO_2 price of around 38 EUR/t CO_2eq would be needed to make the case interesting. As such it is unlikely that CO utilisation as feedstock in the chemical industry will become attractive before at least 2030.

It is important to highlight that our assessment does not take into account initial up-front investments in the carbon capture and transport technologies. For example, costs of building new pipelines for transport have not been taken into account.

In deliverable 4.1 we will provide an assessment at pathway level (as selected under WP2).

[59] The present work did not analyse the individual pathways for which CO/CO_2 could be used as a feedstock but rather focused on assessing the attractiveness of using CO/CO2 in chemicals in comparison to the status quo conditions (e.g. using CO for electricity production or emitting CO_2 and paying ETS prices).

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